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Dynamic Stability Derivatives of Space Shuttle Orbiter Obtained From Wind-Tunnel and Approach and Landing Flight Tests

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SUMMARY

A comparison has been made between ground facility measurements, the aerodynamic design data-book values, and the dynamic damping derivatives extracted from the Space Shuttle orbiter approach and landing flight tests. The comparison covers an angle-of-attack range from 2° to 10° at subsonic Mach numbers. The parameters of pitch, yaw, and roll damping, as well as the yawing moment due to rolling velocity and rolling moment due to yawing velocity are compared.

The comparison showed good agreement between all of the parameters except for the roll damping and the rolling moment due to yawing-velocity parameter which were slightly larger for the wind-tunnel data than for the flight-test results.

INTRODUCTION

The Space Shuttle orbiter approach and landing test (ALT) program has been completed and flight-test data have become available (ref. 1). Since the dynamic stability characteristics of the Space Shuttle orbiter were experimentally determined in wind-tunnel tests at the Langley Research Center and the Arnold Engineering Development Center over a range of proposed flight conditions (refs. 2 to 8), an opportunity exists for the comparison of flight-test data with the ground base test results. The ALT program consisted of five flights. Flights 1 to 3 were with a tail cone over the base of the orbiter and flights 4 and 5 were made with the tail cone removed. All comparisons made herein are for flights 4 and 5 with the tail cone removed.

Because of the nature of the ALT flight program all of the data obtained are subsonic over a Mach number range of 0.37 to 0.56 and over an angle-of-attack range of approximately 2° to 10°. Pitch-, yaw-, and roll-damping data are available from the flight tests, as well as the parameters of yawing moment due to rolling velocity and rolling moment due to yawing velocity. Utilizing these data, a comparison has been made of the existing wind-tunnel test results and the Space Shuttle orbiter design data book (ref. 9) and is presented herein.

SYMBOLS

All data presented are referenced to the body axes system and to a moment reference center location of $0.65l$ as shown in figure 1.

b reference span, meters

$\bar{c}$ wing mean aerodynamic chord, meters

C_l rolling-moment coefficient, $\dfrac{\text{Rolling moment}}{q_\infty Sb}$

C_{l_p} $= \dfrac{\partial C_l}{\partial\left(\dfrac{pb}{2V}\right)}$, per radian

$C_{l_p} + C_{l_{\dot\beta}} \sin\alpha$ roll-damping parameter, per radian

C_{l_r} $= \dfrac{\partial C_l}{\partial\left(\dfrac{rb}{2V}\right)}$, per radian

$C_{l_r} - C_{l_{\dot\beta}} \cos\alpha$ rolling moment due to yaw-rate parameter, per radian

$C_{l_{\dot\beta}}$ $= \dfrac{\partial C_l}{\partial\left(\dfrac{\dot\beta b}{2V}\right)}$, per radian

C_m pitching-moment coefficient, $\dfrac{\text{Pitching moment}}{q_\infty S\bar{c}}$

C_{m_q} $= \dfrac{\partial C_m}{\partial\left(\dfrac{q\bar{c}}{2V}\right)}$, per radian

$C_{m_q} + C_{m_{\dot\alpha}}$ pitch-damping parameter, per radian

$C_{m_{\dot\alpha}}$ $= \dfrac{\partial C_m}{\partial\left(\dfrac{\dot\alpha\bar{c}}{2V}\right)}$, per radian

C_n yawing-moment coefficient, $\frac{\text{Yawing moment}}{q_\infty Sb}$

C_{n_p} $= \frac{\partial C_n}{\partial\left(\frac{pb}{2V}\right)}$, per radian

$C_{n_p} + C_{n_{\dot\beta}} \sin\alpha$ yawing moment due to roll-rate parameter, per radian

C_{n_r} $= \frac{\partial C_n}{\partial\left(\frac{rb}{2V}\right)}$, per radian

$C_{n_r} - C_{n_{\dot\beta}} \cos\alpha$ yaw-damping parameter, per radian

$C_{n_{\dot\beta}}$ $= \frac{\partial C_n}{\partial\left(\frac{\dot\beta b}{2V}\right)}$, per radian

f frequency, hertz

k reduced frequency parameter $\frac{\omega\bar{c}}{2V}$ in pitch and $\frac{\omega b}{2V}$ in roll and yaw, radians

l orbiter body length, meters

M free-stream Mach number

p,q,r angular velocities of model about X-, Y-, and Z-axes, respectively, radians/second

q_∞ free-stream dynamic pressure, N/m^2

R Reynolds number based on body length

S reference area, $meters^2$

V	free-stream velocity, meters/second
X,Y,Z	body axes system
x	moment center
α	angle of attack, degrees
β	angle of sideslip, degrees
δ_{BF}	body flap deflection, positive when trailing edge is down, degrees
δ_e	elevon deflection, positive when trailing edge is down, degrees
δ_{SB}	speed-brake deflection, degrees
ω	angular velocity, $2\pi f$, radians per second

Subscripts:

flt	flight
w.t.	wind tunnel

A dot over a symbol denotes a time derivative; that is, $\dot{\alpha} = \frac{\partial \alpha}{\partial t}$.

VEHICLE DEFINITION AND TEST CONDITIONS

Drawings of the 0.0165-scale model used in the wind-tunnel tests and Orbiter 101 are presented in figures 1(a) and 1(b). Photographs of Orbiter 101 in flight and the scaled model in a test setup are presented in figures 2 and 3, respectively. The wind-tunnel model was a modified 089B version of the orbiter. The planforms of the wind-tunnel model and Orbitor 101 are nearly identical, the only differences in the configurations being a change in the thickness distribution of the wing and for Orbiter 101 a blunting of the orbital maneuvering system (OMS) pods, the addition of a gap between the outboard and inboard elevons, and the installation of a nose probe for the flight tests.

In the flight tests all of the data were obtained for trimmed elevon deflections (always less than 4°) and speed-brake deflections of 3.8° and 43°. All of the wind-tunnel data used in the present comparison were for a 0° elevon deflection and a 10° speed-brake setting. The differences in the speed-brake settings should have negligible impact on the parameters of interest. This is demonstrated by the data presented in reference 2 for speed-brake deflections of 10° and 85° which showed that, even with this extreme difference in speed-brake deflection, there was generally a very small effect on the damping at angles of attack below 10°.

During the ALT flights all of the data were obtained at Mach numbers from approximately 0.37 to 0.56. The aerodynamic data presented in the design data book (ref. 9) show that compressibility effects going from Mach numbers of 0.3 to 0.6 are small; therefore, a comparison of the flight-test damping data (at Mach numbers from 0.37 to 0.56) with the wind-tunnel data (measured at Mach numbers of 0.3) should be valid.

Comparisons of the reduced frequency parameter k and Reynolds number R for the flight tests and the wind-tunnel tests are presented in the following table:

Axis	k, rad		R	
	Wind tunnel	Flight	Wind tunnel	Flight
Pitch	0.0325	0.0014	3.2×10^6	357 to 625 $\times 10^6$
Roll	.112	.0125	3.2×10^6	357 to 625 $\times 10^6$
Yaw	.0605	.0041	3.2×10^6	357 to 625 $\times 10^6$

There is a very large difference in the flight-test and wind-tunnel test Reynolds numbers, but the results of a survey made prior to the wind-tunnel tests showed no existing capability for measuring the damping derivatives at higher Reynolds numbers. As with the Reynolds number, there are large differences between the flight-test and wind-tunnel values of the reduced frequency parameter; however, the limitations of the available test techniques make closer duplication of this parameter impossible.

RESULTS AND DISCUSSION

A comparison of the damping derivatives measured in the wind tunnel with those obtained from ALT flights 4 and 5, as reported in reference 1, is presented in figures 4 to 8. The dynamic derivatives in reference 1 are in the form of combined derivatives so that for the pitch-damping case, the parameter extracted is $C_{m_q} + C_{m_{\dot{\alpha}}}$. For the yawing case where $\cos \alpha$ is assumed to be one, the parameters in reference 1 are $C_{n_r} - C_{n_{\dot{\beta}}}$ and $C_{l_r} - C_{l_{\dot{\beta}}}$. For the rolling case the derivatives are C_{l_p} and C_{n_p} since the terms multiplied by $\sin \alpha$ have been assumed to be zero.

Pitch-Damping Derivatives

A comparison of the pitch-damping data is presented in figure 4. Both the flight and wind-tunnel data show that the configuration exhibits positive pitch

damping (negative values of $C_{m_q} + C_{m_{\dot{\alpha}}}$) over the test angle-of-attack range.

Pitch-damping values from the design data book (ref. 9) are also presented in figure 4 for Mach numbers of 0.40 and 0.60. The results show that the pitch-damping data measured in the wind tunnel are almost within the accuracy band (ref. 1) presented on the figures for the ALT flight data. Generally, the wind-tunnel values of pitch damping are in closer agreement with the flight data than the aerodynamic data-book values.

Yaw-Damping Derivatives

A comparison of the yaw-damping data measured in the wind tunnel with that extracted from the ALT flight data is presented in figure 5. Both the wind-tunnel and flight-test data indicate positive yaw damping at all test angles of attack. Except for 1 data point at approximately 7° angle of attack, the faired wind-tunnel data are within the accuracy band of the flight-test results. This discrepancy at 7° angle of attack could not be explained.

The data from the design data book (ref. 9) show about the same agreement with the flight data as do the wind-tunnel results.

Roll-Damping Derivatives

Presented in figure 6 is a comparison of the wind-tunnel and flight roll-damping data. Both sets of data indicate that the vehicle has positive roll damping at all test angles of attack. The roll-damping values determined from the flight-test results are slightly less than the wind-tunnel values at all except one angle of attack. One explanation for this difference, presented in reference 1, is the possibility of an error of approximately 10 percent in the determination of the roll inertia of Orbiter 101. This could affect all of the flight values of the roll derivatives (static and dynamic). Since the wind-tunnel data and design data-book predictions (ref. 9) are in agreement, comparison of the data-book values with the flight data show this same discrepancy.

Rolling Moment Due to Yawing-Velocity Parameter

A comparison of the rolling moment due to yawing-velocity parameter measured during the ALT flight and the wind-tunnel tests is presented in figure 7. Both sets of data show that the configuration has positive values of the rolling moment due to yawing-velocity parameter throughout the test angle-of-attack range. The comparison of the results shows the same trend as the roll-damping data in that the flight-test values are always less than the wind-tunnel values. The error in the roll inertia, pointed out in the roll-damping discussion, could very easily account for the discrepancy in the rolling moment due to yawing-velocity parameter. The wind-tunnel results and the design data-book values (ref. 9) are in agreement and, therefore, have the same discrepancy.

Yawing Moment Due to Rolling-Velocity Parameter

The yawing moment due to rolling-velocity parameter measured in the flight and wind-tunnel tests is presented in figure 8. The data show that the parameter is nonlinear with angle of attack and has small positive and negative values. The agreement between the ALT flight tests and wind-tunnel results are quite good considering, as pointed out in the appendix of reference 3, that measuring these small damping parameters in the presence of large forces and moments is quite difficult. Compared with the design data-book values (ref. 9), the trends and magnitude of the wind-tunnel data agree much better with the flight data.

SUMMARY OF RESULTS

The results of a comparison of the wind-tunnel measured damping with damping recorded from the Space Shuttle orbiter approach and landing flight tests have shown that:

1. In general, the pitch- and yaw-damping results determined from the wind-tunnel and flight tests agree quite well.

2. The roll damping and rolling moment due to yawing-velocity parameter values measured in the wind tunnel are slightly higher than those determined in flight tests.

3. The yawing moment due to rolling-velocity parameter measured in the wind tunnel and in flight agree quite well considering the difficulty of measuring this parameter in the wind tunnel.

4. Since there are no large discrepancies between the data recorded in the wind tunnel and those recorded from flight tests (the linearity and levels of damping generally agreeing), the wind-tunnel data appear adequate for vehicle and control system design for the subsonic Mach numbers and the low angle-of-attack range of the comparisons.

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February 21, 1980

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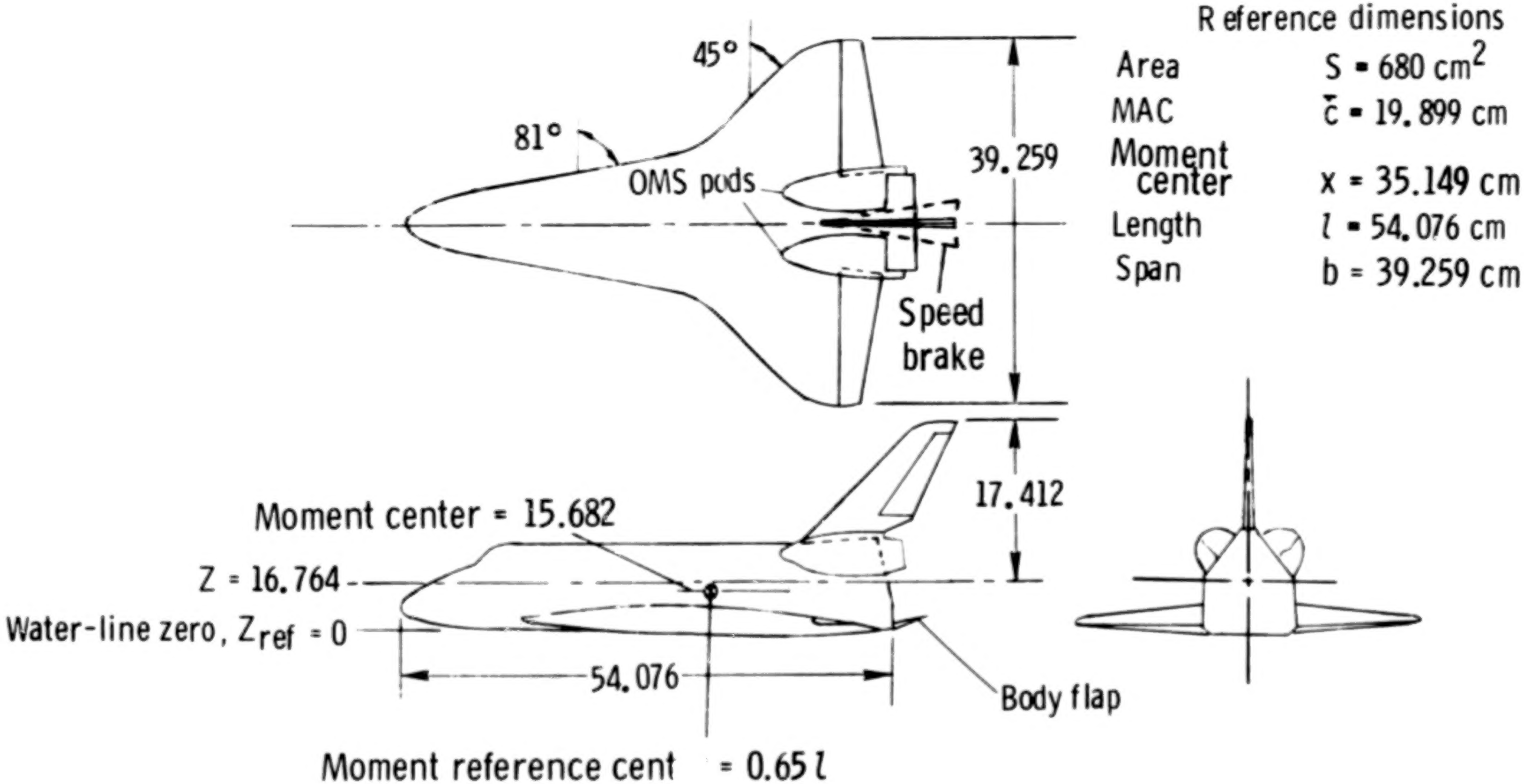
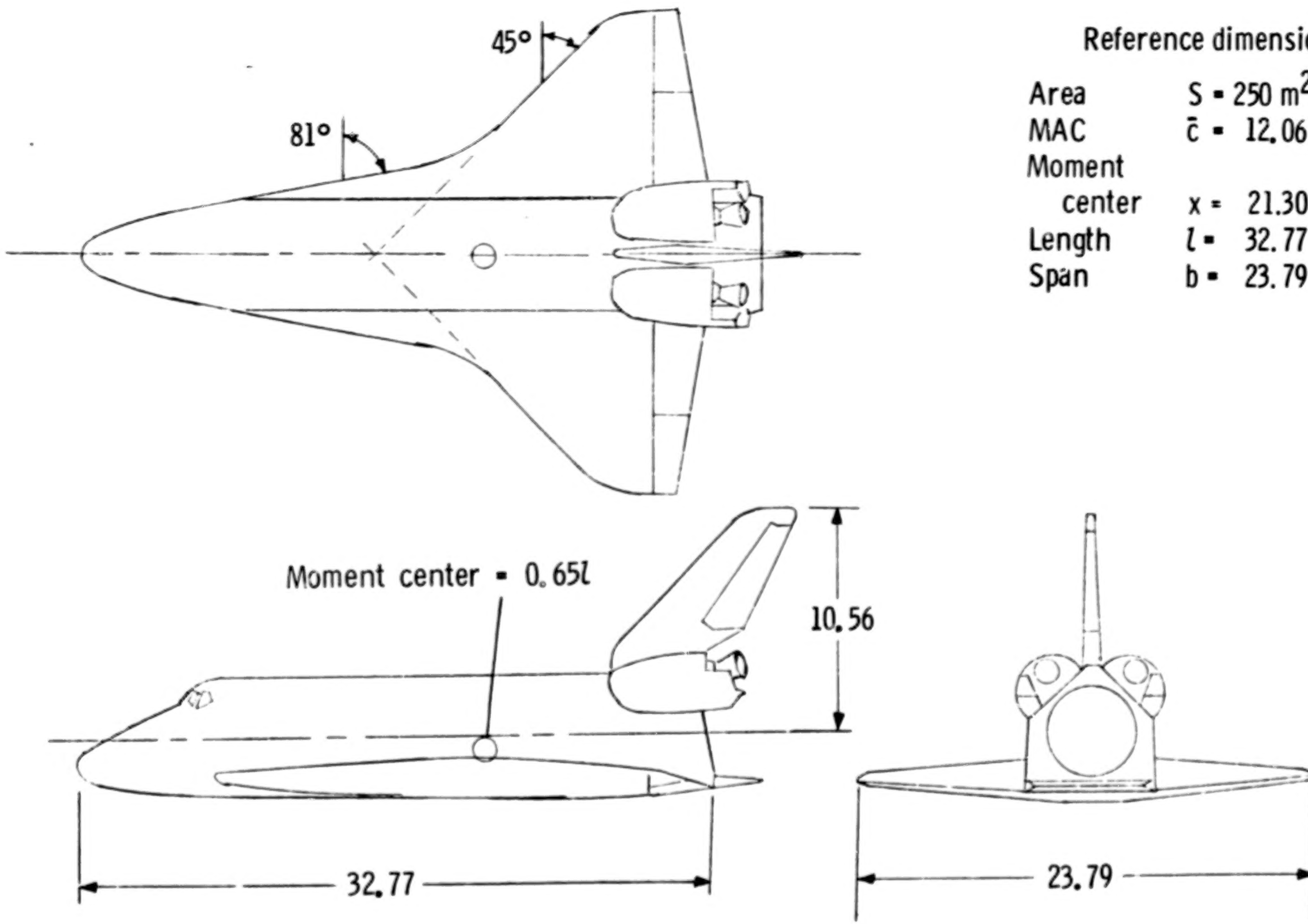


(a) 0.0165-scale wind-tunnel model. All dimensions given in centimeters.

Figure 1.- Sketches of wind-tunnel model and Orbiter 101.



Reference dimensions

Area	$S = 250\ m^2$
MAC	$\bar{c} = 12.06$ m
Moment center	$x = 21.30$ m
Length	$l = 32.77$ m
Span	$b = 23.79$ m

(b) Orbiter 101. All dimensions given in meters.

Figure 1.- Concluded.

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Figure 2.- Orbiter 101 in flight.

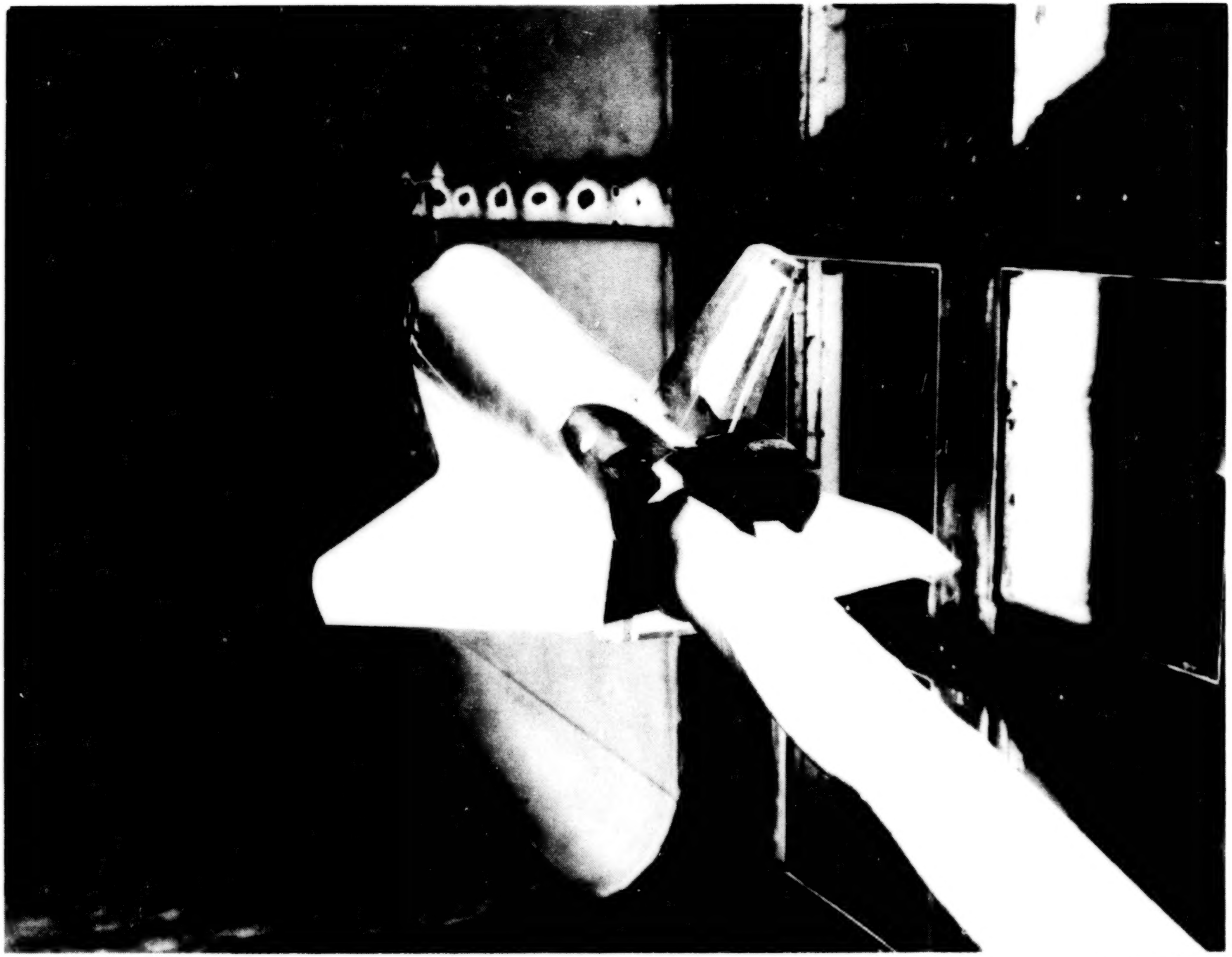

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Figure 3.- Model mounted for forced oscillation tests in the Langley 8-Foot Transonic Pressure Tunnel.

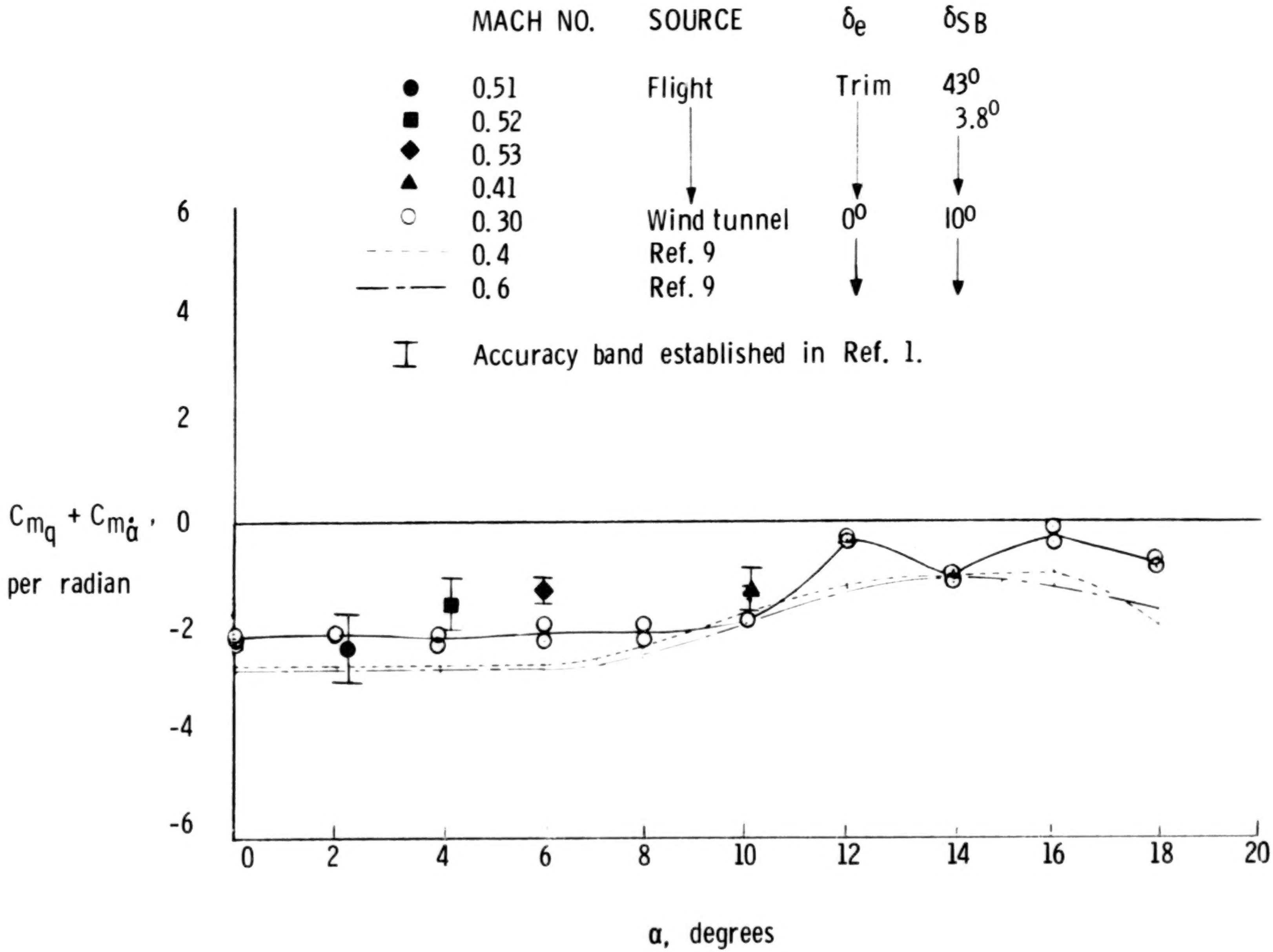

Figure 4.- Comparison of flight and wind-tunnel values of pitch damping. $\delta_{BF} = 0^{\circ}$.

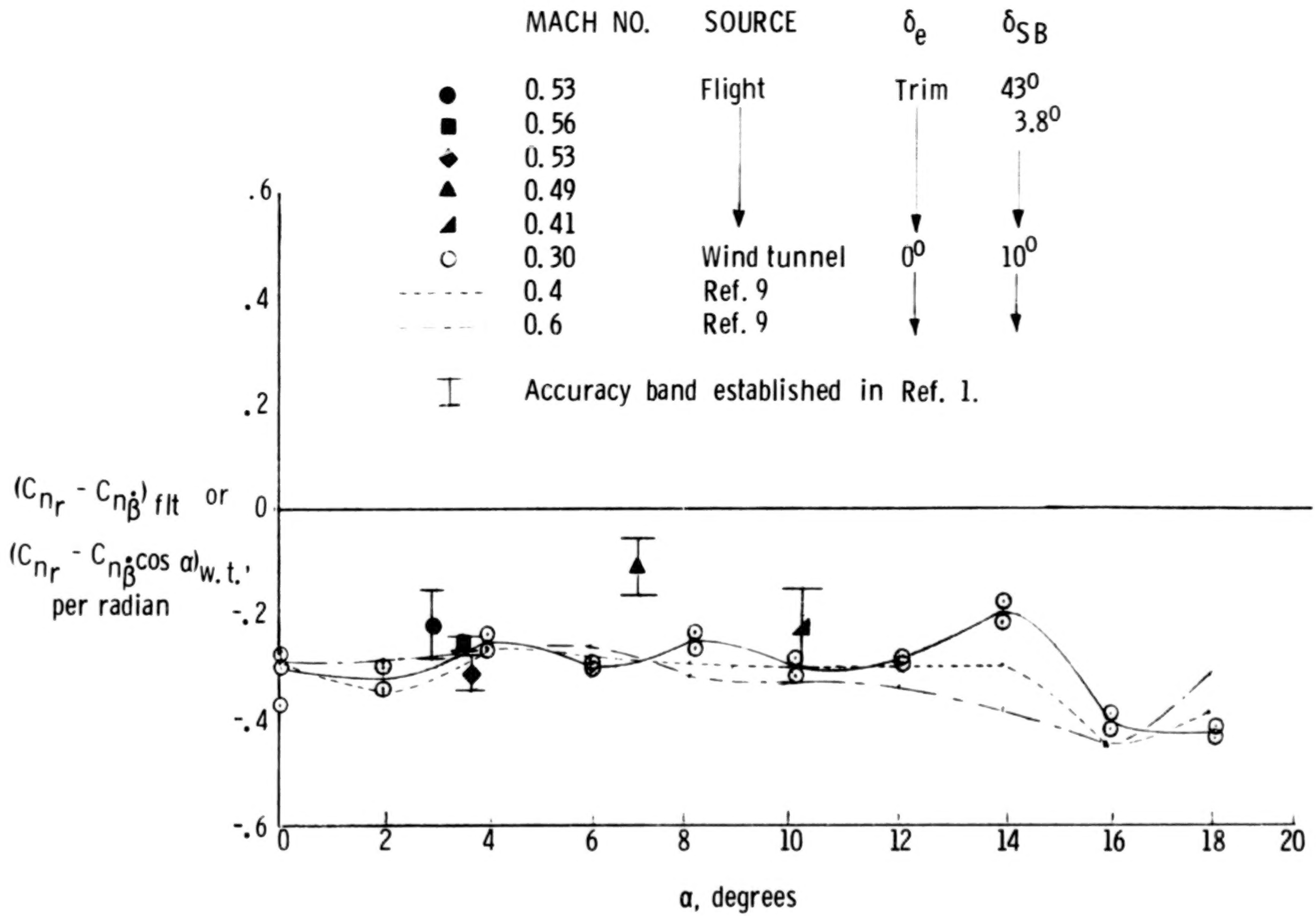

Figure 5.- Comparison of flight and wind-tunnel values of yaw damping. $\delta_{BF} = 0^{o}$.

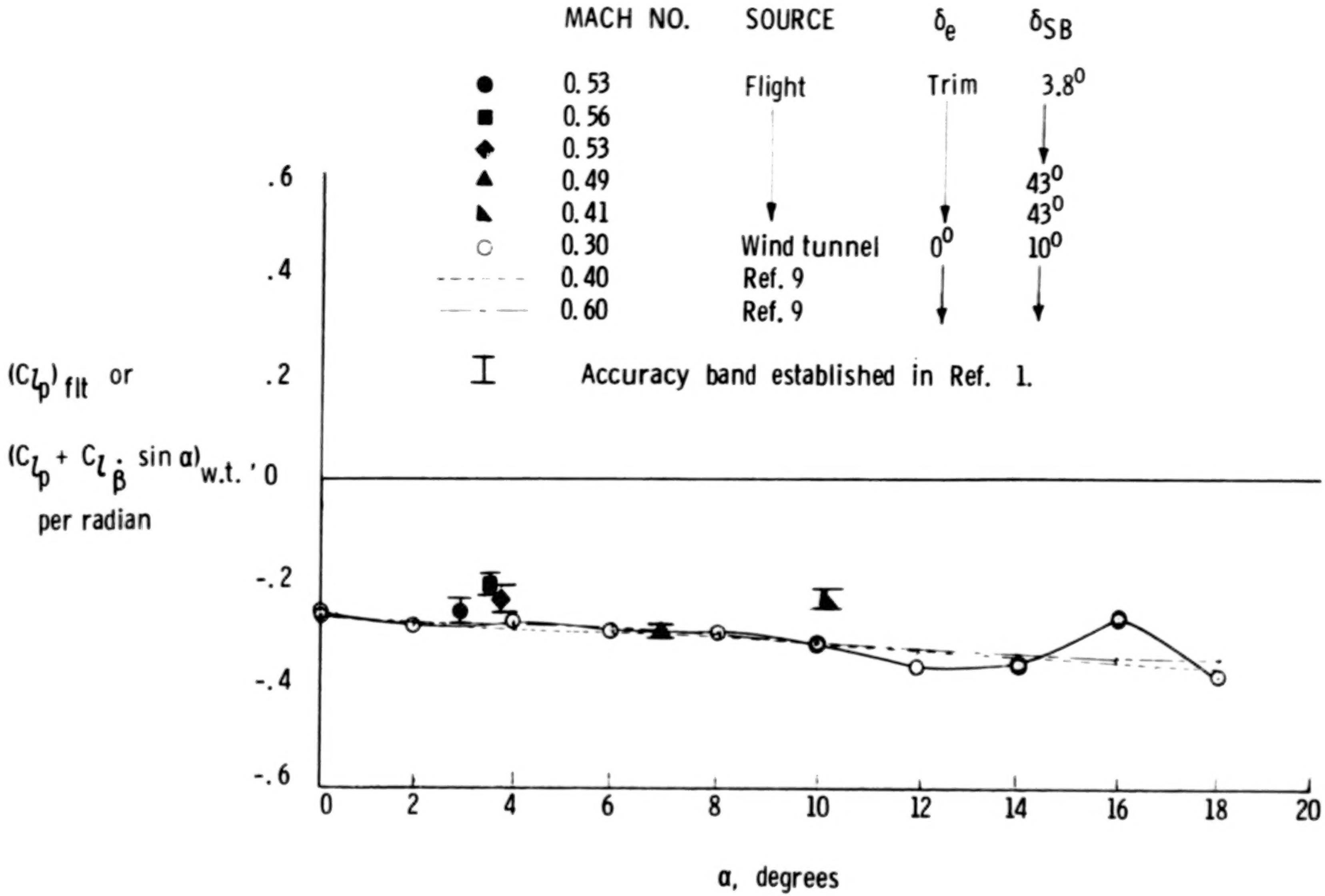

Figure 6.- Comparison of flight and wind-tunnel values of roll damping. $\delta_{BF} = 0^\circ$.

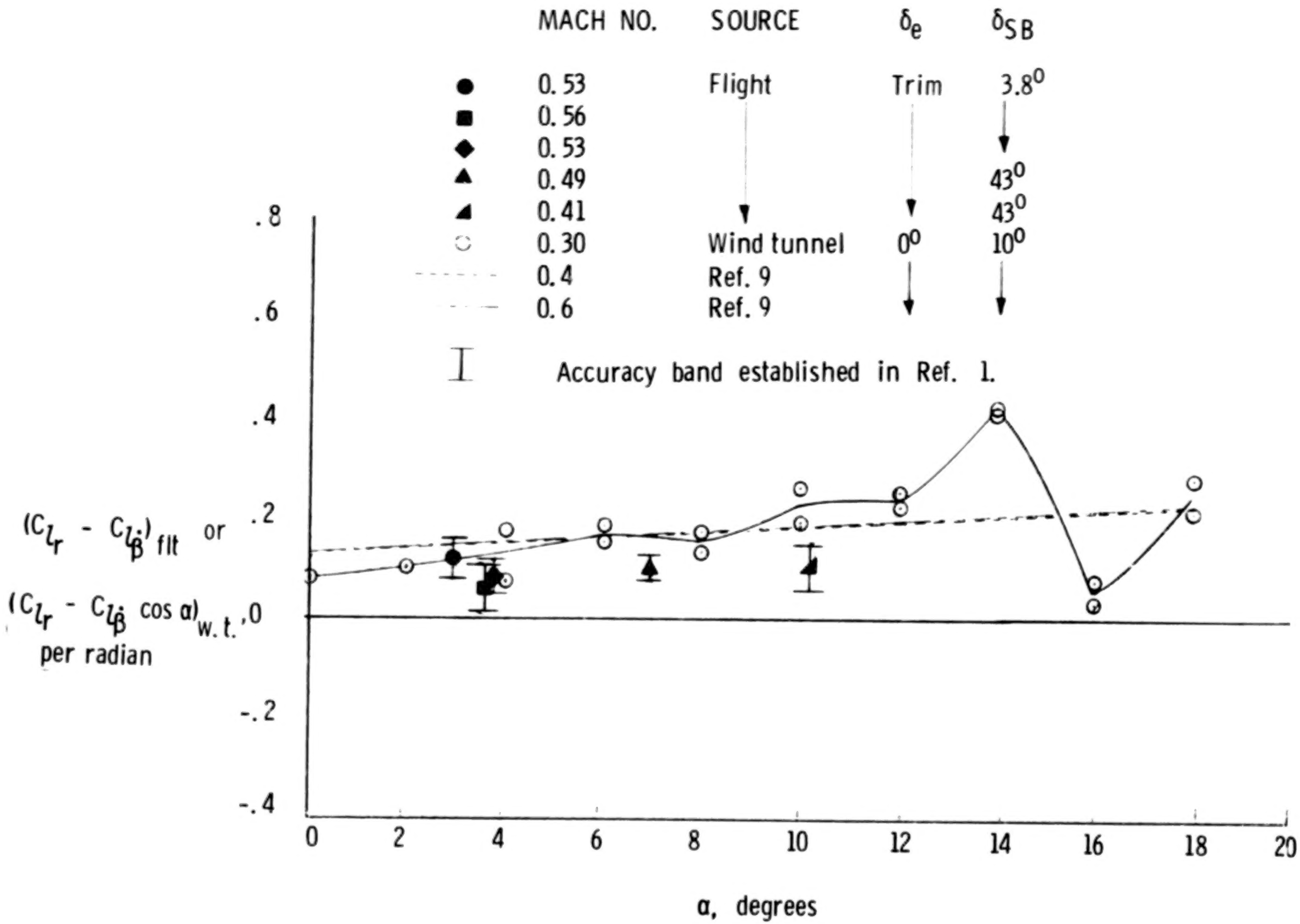

Figure 7.- Comparison of flight and wind-tunnel values of rolling moment due to yawing velocity. $\delta_{BF} = 0^o$.

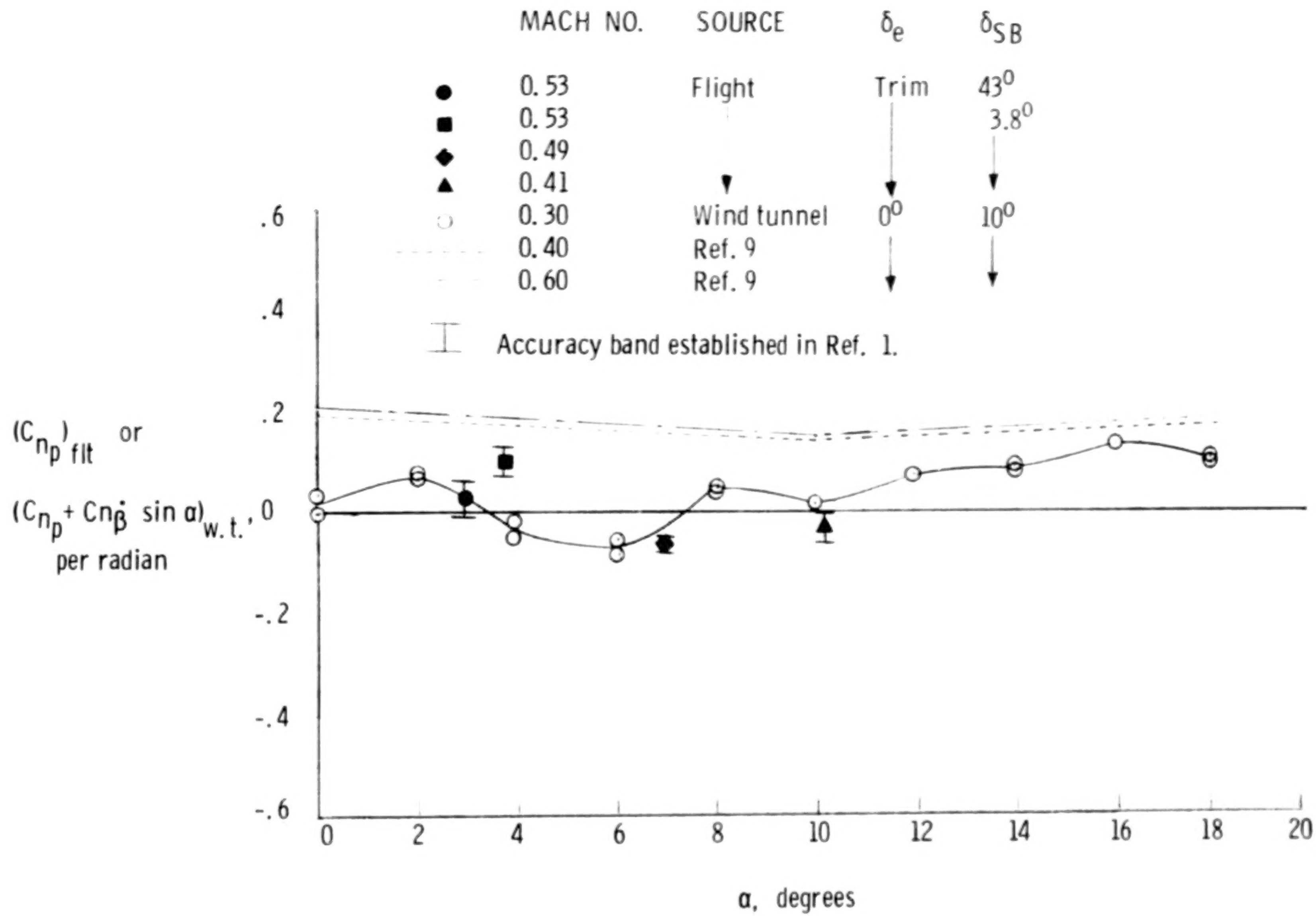

Figure 8.- Comparison of flight and wind-tunnel values of yawing moment due to rolling velocity. $\delta_{BF} = 0^o$.

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16. Abstract

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